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14. ABSTRACT

Imaging of the heliosphere is a burgeoning area of research. As a result, it is awash with new results, using novel applications, and is demonstrating great potential for future research in a wide range of topical areas. The STERREO (*Solar Terrestrial Relations Observatory*) Heliospheric Imager (HI) instruments are at the heart of this new development, building on the pioneering observations of the SMEI (Solar Mass Ejection Imager) instrument aboard the *Coriolis* spacecraft. Other earlier heliospheric imaging systems have included ground-based interplanetary scintillation (IPS) facilities and the photometers on the *Helios* spacecraft. With the HI instruments, we now have routine wide-angle imaging of the inner heliosphere, from vantage points outside the sun-earth line. HI has been used to investigate the development of coronal mass ejections (CMEs) as they pass through the heliosphere to 1 AU and beyond. Synoptic mapping has also allowed us to see graphic illustrations of the nature of mass outflow as a function of distance from the sun—in particular, stressing the complexity of the near-Sun solar wind. The instruments have also been used to image co-rotating interaction regions (CIRs) to study the interaction of comets with the solar wind and CMEs, and to witness the impact of CMEs and CIRs on planets. The very nature of this area of research—which brings together aspects of solar physics, space-environmentphysics, and solar-terrestrial physics—means that the research papers are spread among a wide range of journals from different disciplines. Thus, in this special issue, it is timely and appropriate to provide a review of the results of the first two years of the HI investigations.

15. SUBJECT TERMS

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Two Years of the STEREO Heliospheric Imagers

Invited Review

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Abstract Imaging of the heliosphere is a burgeoning area of research. As a result, it is awash with new results, using novel applications, and is demonstrating great potential for future research in a wide range of topical areas. The STEREO (*Solar TErrestrial RElations Observatory*) Heliospheric Imager (HI) instruments are at the heart of this new development, building on the pioneering observations of the SMEI (Solar Mass Ejection Imager) instrument aboard the *Coriolis* spacecraft. Other earlier heliospheric imaging systems have

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included ground-based interplanetary scintillation (IPS) facilities and the photometers on the *Helios* spacecraft. With the HI instruments, we now have routine wide-angle imaging of the inner heliosphere, from vantage points outside the Sun-Earth line. HI has been used to investigate the development of coronal mass ejections (CMEs) as they pass through the heliosphere to 1 AU and beyond. Synoptic mapping has also allowed us to see graphic illustrations of the nature of mass outflow as a function of distance from the Sun – in particular, stressing the complexity of the near-Sun solar wind. The instruments have also been used to image co-rotating interaction regions (CIRs), to study the interaction of comets with the solar wind and CMEs, and to witness the impact of CMEs and CIRs on planets. The very nature of this area of research – which brings together aspects of solar physics, space-environment physics, and solar-terrestrial physics – means that the research papers are spread among a wide range of journals from different disciplines. Thus, in this special issue, it is timely and appropriate to provide a review of the results of the first two years of the HI investigations.

Keywords Coronal mass ejection · Heliosphere · Solar wind · Co-rotating interaction regions

1. Introduction

Imaging of the inner heliosphere is a field that has recently come to the fore. In the 1970s, single-pixel zodiacal light photometers on the two *Helios* spacecraft, operating in solar orbits with perihelion 0.31 AU, were used to detect coronal mass ejections (CMEs) in the inner Solar System (see *e.g.* Richter, Leinert, and Planck, 1982; Jackson and Leinert, 1985). CME images were constructed from photometers aligned in three directions, which scanned the sky using the rotation of the spacecraft resulting in spatial coverage from which CME structures could be mapped. An additional early technique employed to image the inner heliosphere was the exploitation of the interplanetary scintillation (IPS) observations (Hewish, Scott, and Wills, 1964), in particular from the Cambridge 81.5 MHz array (*e.g.* Gapper *et al.*, 1982). This system produced full-sky images by mapping the scintillation of many radio sources, and demonstrated a capability for the detection of CMEs in the heliosphere and investigation of a range of other aspects relating to heliospheric structure (*e.g.* Tappin, Hewish, and Gapper, 1984; Harrison *et al.*, 1992).

Wide-angle imaging of the inner heliosphere, in visible light, from a spacecraft was enabled by the launch of the Solar Mass Ejection Imager (SMEI) aboard the *Coriolis* spacecraft in 2003 (Eyles *et al.*, 2003; Jackson *et al.*, 2004). This instrument provided a thousand-fold increase in spatial resolution over the *Helios* photometer data and an order of magnitude better time resolution. SMEI maps the entire sky using three baffled camera systems each scanning a 60 degree slice of the sky as the spacecraft moves around the Earth. This instrument has pioneered full-sky mapping aimed particularly at the detection of CMEs propagating through the inner heliosphere.

In many ways, with the subsequent launch of the two Heliospheric Imagers (HIs) (Harrison *et al.*, 2008; Eyles *et al.*, 2009) aboard NASA's twin *Solar TErrestrial RElations Observatory* (STEREO) spacecraft, this field has come of age. Building directly on some of the technology developments from SMEI, the HI instruments provide a combination of routine wide-angle heliospheric mapping from a location out of the Sun-Earth line. Hence, these instruments are unique in their ability to image those events directed towards the Earth. Indeed, with fields of view which cover the range from 4 to 89 degrees elongation from the Sun, the HI instruments provide a view of the passage of CMEs from the outer corona to

well beyond the Earth. Such observations represent a major milestone in investigations of the influence of solar activity on the Earth and human systems.

The HI instruments are part of the Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) package of remote sensing instruments aboard STEREO, designed to study the solar disk, the corona and heliosphere – from the Sun's chromosphere to the Earth and beyond. The SECCHI package is described by Howard *et al.* (2008).

The STEREO spacecraft were launched on 26 October 2006 and inserted into near 1 AU solar orbits, one leading and the other lagging the Earth. The leading spacecraft is labelled STEREO-A (Ahead) and the lagging spacecraft, STEREO-B (Behind). The orbital configuration is such that each spacecraft recedes from Earth by 22.5 degrees per year, as measured by the spacecraft-Sun-Earth angle. The wide spacecraft-Sun-spacecraft angle achieved as the mission matures not only enables the detection of ejecta propagating along the Sun-Earth line, it also enables 3D imaging by remote-sensing instruments.

Following insertion of the spacecraft into their heliocentric orbits, the HI instrument doors were opened on 13 December 2006 (STEREO-A) and 11 January 2007 (STEREO-B). After commissioning, the HI instruments started their science operations phase in April 2007. At the time of writing, STEREO and the HI instruments have been in space for two years and we have had 19 months of scientific operation.

The HI operational and geometrical and characteristics are shown in Table 1 and Figure 1. Each HI instrument includes two wide-angle refractive telescopes, known as HI-1 and HI-2. Using the labels A and B for the Ahead and Behind spacecraft, respectively, we have four telescopes which we denote HI-1A, HI-2A, HI-1B, and HI-2B. Both HI-1 telescopes are

Table 1 Basic parameters of the HI telescopes (from Harrison *et al.*, 2008)

	HI-1	HI-2
Direction of Centre of Field of View from Sun Centre	14 degrees	53.7 degrees
Angular Field of View	20 degrees	70 degrees
Angular Range Along Centre of Field of View from Sun Centre	4–24 degrees	18.7–88.7 degrees
Image Array (2 × 2 binning)	1024 × 1024	1024 × 1024
Image Pixel Size (2 × 2 binning)	70 arc sec	4 arc min
Band Pass	630–730 nm	400–1000 nm

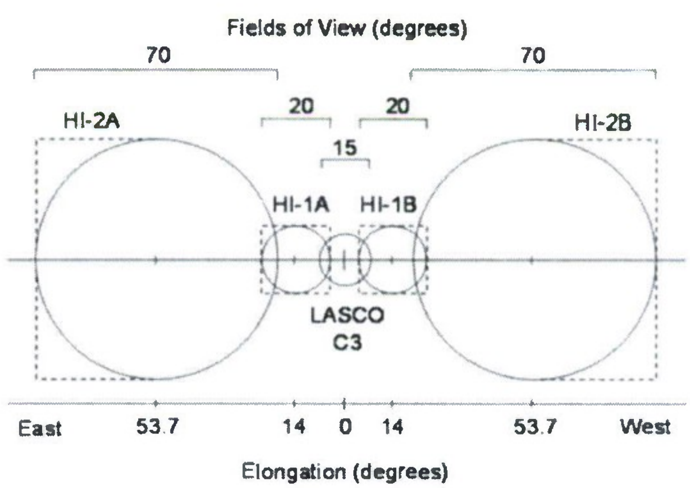

Figure 1 The fields of view of the HI telescopes, compared with the SOHO/LASCO C3 instrument field of view (adapted from Eyles *et al.*, 2009). Although the HI instrument response is optimised for the circular fields shown, of diameter 20 and 70 degrees for HI-1 and HI-2, respectively, the square format of the CCD detectors result in some response in the regions marked by the dotted lines.

identical as are both HI-2 telescopes. Although 2k × 2k CCD pixel detector arrays are used for each telescope, the images are 2 × 2 binned on board to give 1k × 1k images.

Figure 1 shows the geometrical layout of the HI telescope fields of view, which emphasises the scale of the new imaging capability compared to that of the coronagraph images to which we have become accustomed and shows how much of the inner heliosphere is covered by the HI instruments. The extent of the field of view of the outer (C3) Large Angle Spectrometric COronagraph (LASCO: Brueckner *et al.*, 1995) on the *Solar and Heliospheric Observatory* (SOHO) spacecraft is shown to facilitate such comparison. The abscissa is elongation with respect to Sun-centre, both east and west of the Sun. The Sun is, of course, at the centre of the LASCO C3 15-degree field. The elongation angles of the HI telescope boresights and the extents of their fields of view are identified. Although Figure 1 is shown as one flat diagram, for illustration, the spacecraft are not co-located, but are separating with time. The HI-A and HI-B fields will in fact cover common areas of the heliosphere when the spacecraft are well separated.

Baffle systems ensure that scattered light from the Sun is reduced to a level of less than 10^{-13} of the solar brightness allowing the detection of point sources of 12th to 13th magnitude (Eyles *et al.*, 2009). The significant F-coronal signal can be removed using an analysis of the minimum intensities on a pixel by pixel basis over a sequence of images. Thereafter, the HI cameras are perfectly capable of detecting CMEs in the inner heliosphere, yet are also well able to detect planets, comets, asteroids, stars, and other phenomena. This has resulted in a wide range of potential scientific applications which we explore in the following sections. We have to stress that this is only a fraction of the work being done using HI observations but it is a useful guide to the nature and extent of the solar and solar-system research being addressed.

More aspects of the HI characteristics, performance, and operation are included in Eyles *et al.* (2007, 2009), Brown, Bewsher, and Eyles (2009), and Harrison *et al.* (2008), and are beyond the scope of this report. We include here only the most basic information required to understand the images and plots which appear in this review.

2. Coronal Mass Ejections

The HI instruments were designed principally to study CMEs in a region extending from the outer corona well into interplanetary space. Therefore, this encompasses both the phenomena that we traditionally term CMEs and Interplanetary CMEs (ICMEs). The detailed relationship between the two is unclear, mainly due to the markedly different observational approaches used to date. In the past, we have loosely defined the former as ejecta detected close to the Sun using coronagraphs, and the latter as ejecta usually detected using *in situ* particle and field measurements in interplanetary space. It is, however, generally accepted that an ICME is the interplanetary counterpart of a CME. In essence, we are now able to make significant strides in marrying the CME and ICME paradigms. Here, we adopt the policy of calling all of these events 'CMEs', irrespective of distance from the Sun.

HI enables the tracking of CMEs through the solar system – in particular those directed towards Earth but also those that impact other planets and solar system bodies. Moreover, it facilitates the investigation of the 3-dimensional structure of CMEs.

One of the first observations of CMEs in the heliosphere made using the HI instruments was from 24 – 26 January 2007, and was reported in detail by Harrison *et al.* (2008). Figure 2 shows this event in one of the HI-1A frames.

The most important issue with regard to this observation is the fact that the capability of HI to detect CMEs in the heliosphere was proven. Figure 2 shows a CME whose outer edge

Figure 2 An HI-1A image taken on 25 January 2007. This image is 20 degrees across (80 solar radii in the plane of the sky) and the Sun is four degrees off the right of the frame. The planets Venus and Mercury can be seen (lower left and right, respectively) and a CME is clearly expanding into the right-hand side of the image. (From Harrison *et al.*, 2008).

is about 10 degrees elongation from Sun centre, or 39 solar radii from the limb in the plane of the sky. Subsequently, it was seen to propagate through the HI-1A field but, perhaps of more significance, was then detected in the outer HI-2A field. We note that further studies (Lugaz *et al.*, 2008; Webb *et al.*, 2009) showed this interval in fact involved more than one CME.

Expanding CMEs will reduce in intensity as they propagate outwards, so it is a challenge to extract CME signals farther and farther from the Sun. However, the outer loops of the 24 – 26 January 2007 CME reported by Harrison *et al.* (2008) can be seen in Figure 3 propagating into the HI-2A field. Whilst the image shown in Figure 2 is processed such that the F-corona is subtracted, the brightness of the CME relative to the background diminishes such that we have resorted to another technique, namely image differencing, to highlight the CME in the HI-2A field of view.

To summarise, the HI data revealed a CME which was tracked from 4 to over 40 degrees in elongation from the Sun (171 solar radii from the solar limb perpendicular to the spacecraft-Sun line). The event was ascending at about 600 $\mathrm{km\,s^{-1}}$ in the plane of the sky and was readily associated with a CME detected in the outer corona using the SOHO coronagraph.

Following this first announcement, studies involving a number of CMEs detected using the HI data have been published or are in press at the time of writing. For example, a variety of events are shown by Dorrian *et al.* (2008), Lugaz *et al.* (2008), Davies *et al.* (2009), Eyles *et al.* (2009), Harrison *et al.* (2009), Harrison, Davis, and Davies (2009), Rouillard *et al.* (2009a), and Webb *et al.* (2009). Figures 4 and 5 show a selection of CMEs reproduced from a couple of these papers.

A number of these papers refer to the Thomson sphere (see Vourlidas and Howard, 2006). Coronagraphs (including the HI instruments) detect density enhancements which are visible due to Thomson scattering of photospheric light off free electrons. The region of greatest scattering actually describes a sphere where the Sun and the observer (in this case a STEREO spacecraft) are located on the opposite ends of one diameter. This has a number

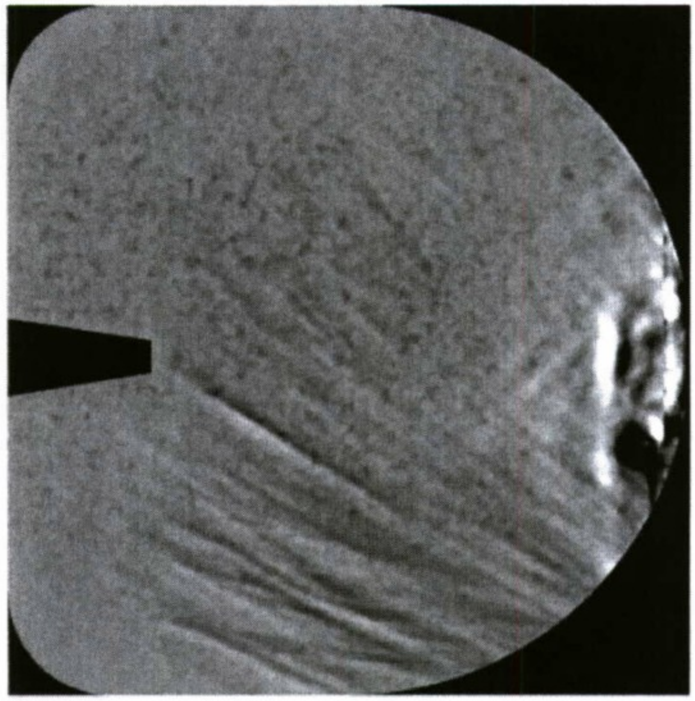

Figure 3 The 24 – 26 January 2007 CME in the HI-2 field. The multiple-loop structures of one or more CMEs can be seen in the right hand side of the frame. The striations in the lower half of the frame are due to the huge structured tail of comet McNaught (see later section) passing through the field of view. The feature on the left hand centre is an occulter designed to block the Earth in the earliest stages of the mission. (From Harrison *et al.*, 2008).

Figure 4 The 5 November 2007 CME in the HI-1A field. The Milky Way can be seen to the left of the frame, with Jupiter at centre-left. Stars down to 12th or 13th magnitude can be seen. A CME is evident on the right hand side. (From Eyles *et al.*, 2009).

of consequences. Near the Sun, in traditional coronagraph fields, the part of the sphere that is relevant is near to the plane of the sky centred on the Sun. With the extended fields of HI, and indeed SMEI, the Thomson sphere becomes far more significant. Features can fade or be enhanced simply because of their location with respect to the Thomson sphere and that requires careful interpretation. For example, Manchester *et al.* (2008) have modelled

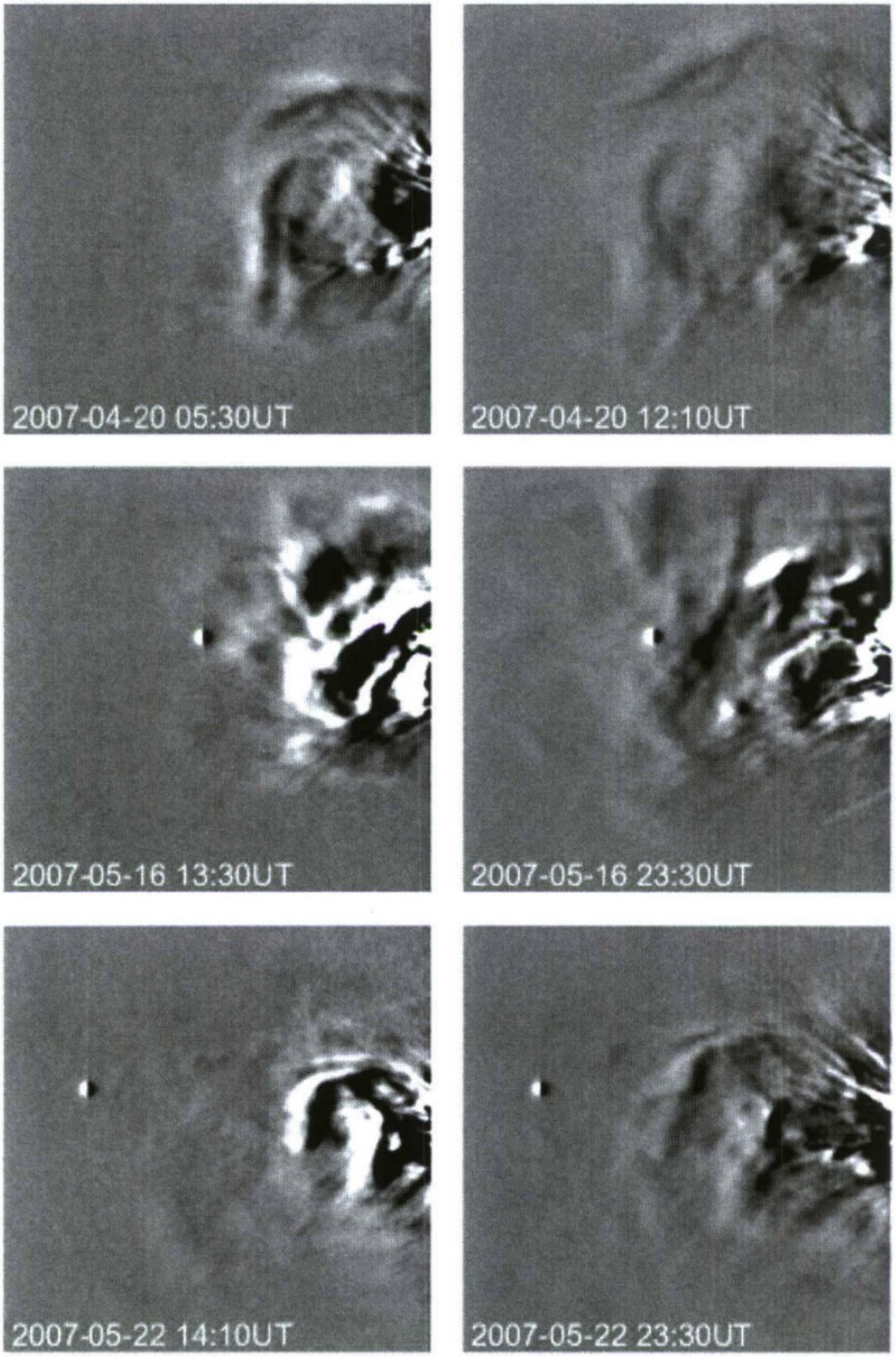

Figure 5 CME events observed in April and May 2007, from Harrison *et al.* (2009). In each case, two frames are produced showing the development of the CME in the HI-1A frame over many hours.

the evolution of CME brightness in the HI-2 fields of view and predicted two features due to the effects of the Thomson sphere: the apparent deceleration (called "stall" by the authors) of a CME front observed by HI-2, and the appearance of a second front due to multiple crossings of the sphere by a CME. This illustrates the importance of considering the effects of the Thomson sphere, and many of the CME papers do indeed comment on this and in some cases provide detailed interpretations.

Other aspects of CME observations are returned to in later sections. However, of particular interest here is the tracking of CMEs through the heliosphere and in that context we report on the work of Webb *et al.* (2009). As mentioned above, Harrison *et al.* (2008) tracked a CME on 24 – 26 January 2007 from 4 to over 40 degrees elongation, using the HI telescopes. Webb *et al.* have studied the same period and have incorporated data from the SOHO LASCO coronagraph and the SMEI instrument, as well as observations from the set of SECCHI instruments aboard STEREO. Thus, the Webb *et al.* (2009) study is one of the first multi-observatory analysis utilising the STEREO data in an attempt to study the development of the CME through a large portion of the inner heliosphere, and also comparing that development to available models. Both Webb *et al.* and Lugaz *et al.* (2008) who also study this interval reveal that the sequence involves more than one CME.

Specifically, Webb *et al.* studied the early evolution of these CMEs using the LASCO C2 and C3 and SECCHI COR1 and COR2 coronagraphs and followed the development of the events through the inner heliosphere using the HI and SMEI instruments. The HI field of view lies within the SMEI field of view (which covers the full-sky except for the region below 20 degrees elongation) and, thus, both instrument sets can observe the same CMEs in the heliosphere. The structural and kinematic evolution of the CMEs was compared to drive/drag kinematic, 3D tomographic reconstruction, the HAFv2 kinematic, and the ENLIL MHD models.

Figure 6 presents an HI-2A image and a simultaneous SMEI image from 26 January 2007, showing the CME structure moving east of the Sun at about 30° elongation. Figure 7 shows elongation-time profiles for the features that could be tracked progressively outwards: the two LASCO CMEs, and six HI and four SMEI-associated brightness enhancements at different position angles. Periods of missing HI and LASCO data, obscuration by the extensive tail of comet McNaught and by the Moon, and particles in Earth orbit made distinguishing and joining separate events difficult. Webb *et al.* compared the models with the data tracks to help us understand the CME propagation. The results were encouraging in that the four models generally agreed on both the kinematic evolution and appearance of the events.

This study demonstrates that combining data from the HI and SMEI instruments adds an abundance of information on a given event. The results show the importance of large-scale views of CMEs as they propagate from the Sun, especially for understanding their 3D nature and their interactions with the existing solar wind structures through which they move. CME-associated features were observed with the combination of instruments from STEREO and SOHO out to $\sim$50° elongation. With the addition of SMEI, Webb *et al.* were able to track CME structures out to $\sim$100° elongation. The study also emphasises the importance of using both observations and models to better understand the structure and propagation of CMEs in the heliosphere. For the same CME events, Lugaz *et al.* (2008) present a simulation of the sequence. It is clear from the work of Webb *et al.* and Lugaz *et al.* that the models help us to understand the gross propagation characteristics involved in interplanetary shocks, overall kinematics, and interactions both between CMEs and with the background solar wind structures. The observations help constrain the models and adjust their key parameters such as initial conditions, geometry, and speed.

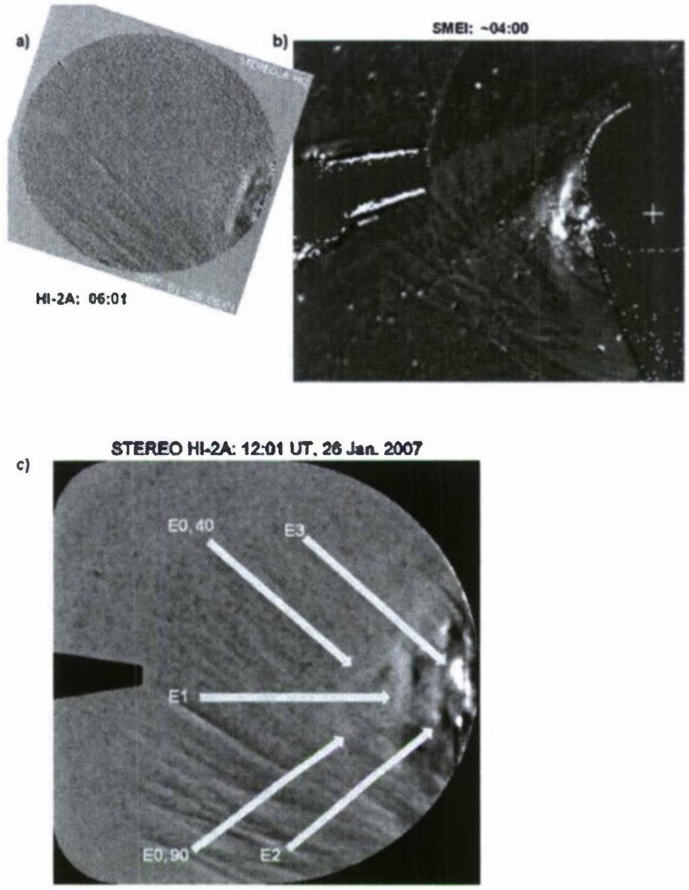

Figure 6 Images derived from the SMEI (b) and HI-2A data (a, c), showing the CME on 26 January 2007. The five arrows on panel c mark the five HI-2A fronts tracked in Figure 7. (From Webb *et al.*, 2009).

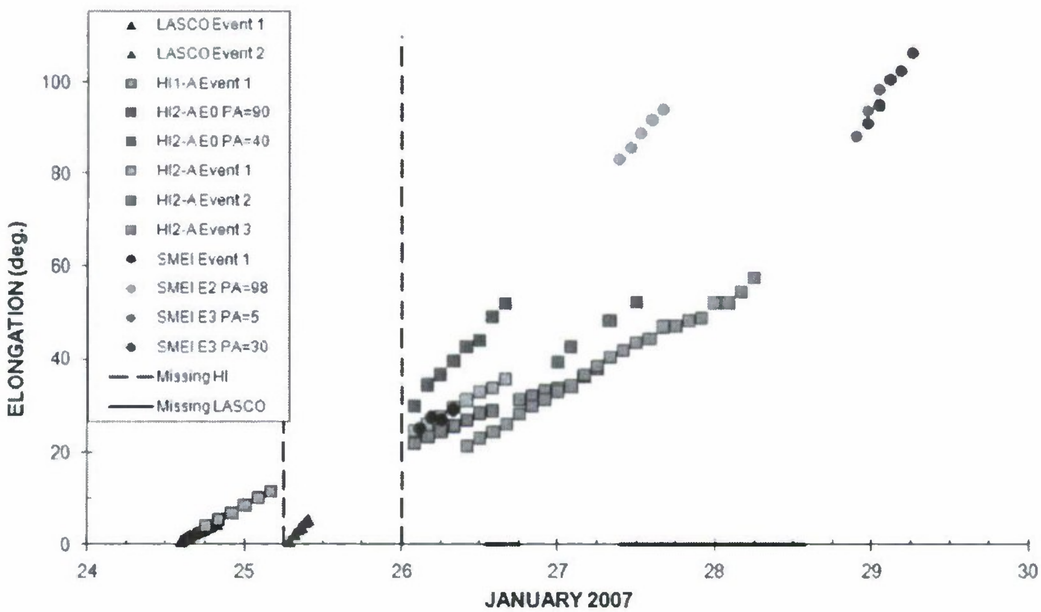

Figure 7 Elongation-time profiles of CME fronts observed from 24–30 January 2007, combining data from LASCO, HI and SMEI. (From Webb *et al.*, 2009).

Harrison *et al.* (2009) reviewed recent research into CMEs in the heliosphere, and embarked on a study to interpret the HI data with reference to the conclusions of this work. Referring to the review of Crooker and Horbury (2006), and the work of Gosling *et al.* (1987), McComas (1995) and others, they investigated several issues. The *in situ* data provide evidence for long-term connectivity to the Sun. Noting that the *in situ* datasets can be used to imply connectivity even out to Jupiter-like distances, the HI datasets were presented as supporting evidence that we do not see the magnetic 'pinching off' of CMEs during their passage through the extensive HI fields of view. Below such a pinching-off region one would expect to see large-scale loops descending as field lines close-down, and, above this, the CME itself would become completely detached from the Sun, as a large-scale plasmoid.

In the absence of any evidence for such pinching off, and noting the fact that the heliospheric magnetic field density does not increase with time, Harrison *et al.* (2009) considered the observational evidence for interchange reconnection in the HI data. This is a process where the closed field lines of the CME, whose front has propagated some distance from the Sun, can reconnect with adjacent open field lines. Such reconnection occurs close to the Sun, at one footpoint of the CME structure. Thus, we have a model that does not require magnetic pinching off directly behind the ascending CME. Observationally, with an interchange reconnection process, we are now looking for ascending, narrow V-shaped structures or blobs emanating from the footpoints of long-erupted CMEs. Indeed, Harrison *et al.* (2009) presented some preliminary analyses of narrow V-shaped events which may be evidence for such events, and this has been investigated further in relation to the CME onset question by Harrison, Davis, and Davies (2009).

In short, the HI observations of CMEs in the heliosphere show support for the established interpretation of CMEs in the heliosphere using *in situ* data. This includes the suggested long-term connectivity of CMEs to the Sun, and also the rejection of the traditional magnetic pinching off of CMEs in favour of a process such as interchange reconnection.

3. A Global View of the Ejection Processes

The synoptic nature of the HI dataset has been exploited by Davies *et al.* (2009) to extend a well-established technique developed for coronal analysis by Sheeley *et al.* (1999), by producing elongation-time plots that reveal the nature of solar transient activity over a far more extensive region of the heliosphere than was previously possible from coronagraph images.

Figure 8 presents such an elongation-time plot, which is produced by stacking the intensities along the centre-line of a sequence of combined HI-1A and HI-2A running difference images between 6 and 26 July 2007. The figure extends in elongation from the sunward edge of the HI-1A field-of-view to the edge of the HI-2A occulter, a coverage of 4 to 74 degrees along the centre line which corresponds closely to the ecliptic throughout the period.

A plethora of outward-propagating solar transients, discernable as inclined tracks in such an elongation-time format plot, are revealed. The variety of forms exhibited by these signatures suggests a diversity of propagation characteristics manifested by solar ejecta. To put this in perspective, analogous plots produced from coronagraph data extend only to approximately eight degrees. Thus, we now have a graphic view of the structure of ascending phenomena in a large portion of the inner heliosphere out to Earth-like distances.

A striking feature of the elongation-time plot is the distinct reduction in the number of outward-propagating solar transients that are observed at increasing elongations; this is most likely due, at least in part, to the reduction in their brightness below the observational sensitivity as they expand radially outward and merge into the background solar wind structure.

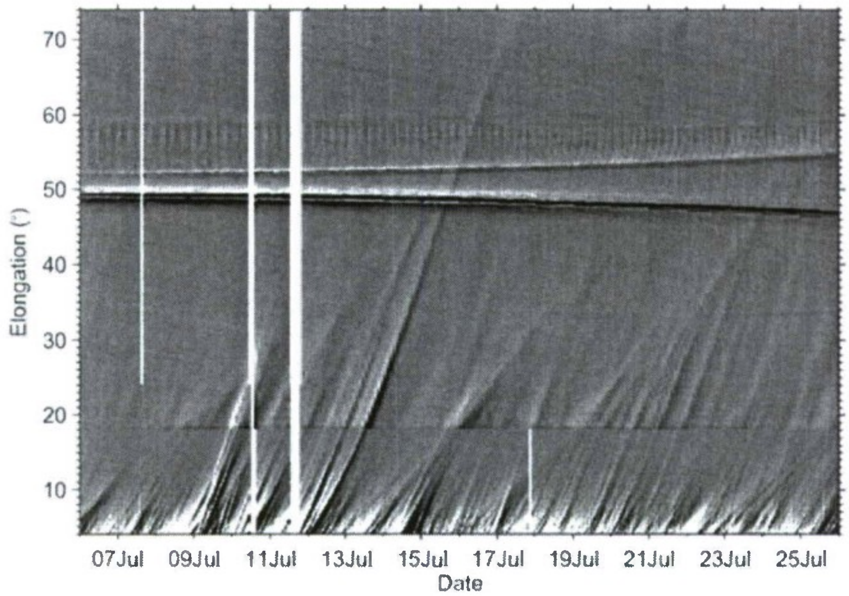

Figure 8 An elongation-time plot showing a 'global' picture of ejecta in the 4 – 74 degrees elongation range from 6 July to 26 July 2007 from HI on STEREO-A. The approximately horizontal features at around 50 degrees elongation are due to the presence of Venus and an associated optical ghosting effect, drifting through the field of view. The discontinuity at 18 degrees corresponds to the inner edge of the HI-2A field, with HI-2A observations being plotted where the HI-1A and HI-2A fields of view overlap. (From Davies *et al.*, 2009).

This simplification of the solar wind structure away from the Sun is surely a fundamental feature of the inner heliosphere and, whilst it may be anticipated, direct imaging of this simplification with elongation using the HI instruments is a significant result.

One transient, which enters the HI-1A field of view near 00:00 UT on 12 July, is conspicuous in that it can be clearly tracked across the entire elongation range covered by Figure 8. This feature corresponds to the dense core of a CME launched from the eastern solar hemisphere on the previous day; the fainter tracks of a complex hierarchy of overlying loops lead the core signature. Analysis of the non-linear shape of the trajectory of the CME core material, which is a geometrical effect rather than indicating any real acceleration/deceleration of the structure (see below, and Sheeley *et al.*, 2008a, 2008b and Rouillard *et al.*, 2008), provides an estimate of the longitude of propagation of the CME, as well as its radial velocity. The former is consistent with this CME being associated with an active region located near the east limb. Moreover, this trajectory shows that the CME can be clearly observed propagating out to distances of 1.1 AU thereby validating the efficacy of the HI instruments in the study of the propagation of solar transients to and beyond Earth-like distances.

These elongation-time plots, commonly known as J-plots, have become a vital product of the HI instrument investigations.

4. Imaging Co-rotating Interaction Regions (CIRs), and CME-CIR Interactions

Images taken from a single viewpoint can only approximate true heliocentric distances. A more precise determination of the positions and propagation paths of solar transients should recognise that observations are projected onto the celestial sphere centred at the observer. In particular, transients propagating outward at approximately constant speed away

from the Sun will appear to accelerate or decelerate depending on their trajectory with respect to the plane of the sky as viewed by the observer.

This effect of projective geometry was described and utilised by Rouillard *et al.* (2008) and Sheeley *et al.* (2008a, 2008b) to determine the trajectory of small-scale transients in the solar wind using the so-called J-plot mapping technique presented in the previous section. In particular, the authors demonstrate that small-scale transients emitted by a co-rotating source at the coronal base, such as the plasma blobs continually released by helmet streamers, will leave converging/diverging tracks in STEREO-A/B J-plots, respectively. It turns out that this property is a truly valuable one, in particular, for the detection of CIRs in the HI images (Rouillard *et al.*, 2008, Sheeley *et al.*, 2008a, 2008b).

Sheeley *et al.* (2008b) made direct comparison of HI images with *in situ* measurements of the solar wind in the first year of the mission, when the Earth and STEREO-A were in the field of view of HI-2 on STEREO-B. The authors show clearly that the most common structures seen in HI-2 fields of view during the years of solar minimum are in fact co-rotating interaction regions (CIRs). This is illustrated in Figure 9 (from Sheeley *et al.*, 2008b) which presents five HI-2B differenced frames, from July 2007. Several of these images show clear CIR-associated plasma density waves approaching the Earth from the left-hand (near-Sun) side; the Earth is the bright feature to the right of the centre of each frame, which is blooming from the top to bottom of the frame (*i.e.* the excess charge in the CCD pixels containing the Earth spills into adjacent pixels along the vertical column). CIRs occur when fast solar wind catches up slow solar wind during their radial expansion (*e.g.* Lee, 2002). The interaction of the fast wind with the slow solar wind forces a compression region with enhanced density and interplanetary magnetic field. *In situ* magnetic field and solar wind observations from the same period in July 2007, from the near-Earth ACE spacecraft, are shown in the lower part of Figure 9. Each of the CIR-associated plasma density waves imaged by HI can be matched to a corresponding characteristic *in situ* signature of a CIR, in particular the enhanced solar wind density (top line plot) and elevated magnetic field strength (fourth line plot).

Sheeley *et al.* (2008a, 2008b) and Rouillard *et al.* (2008) showed that, in fact, CIRs can be observed in STEREO HI difference images when small-scale transients, such as streamer blobs, become compressed inside them. Building on the analysis of Sheeley *et al.* (2008b), Rouillard *et al.* (2008, 2009b) present a comparison of a clear CIR plasma wave observed by HI with simultaneous *in situ* observations of the solar wind. The geometry of the CIR wave in the HI-2 images compares well with that inferred from the *in situ* observations of the topology of the magnetic field. Moreover, the authors show that a small-scale transient, consisting of a small-scale flux rope, is embedded inside the CIR. The presence of a small-scale transient appears to be a requirement for CIRs to be observed in running difference images. The CIR structure is observed to vary in brightness due to the presence of small-scale transients such that CIRs are visible in running difference images (Rouillard *et al.* 2008, 2009b). This property of HI-differenced images has highly significant space-weather applications; white-light imagers could be used to detect CIRs with small- or large-scale transients embedded in them during their transit from the Sun to the Earth. Burlaga, Behannon, and Klein (1987) have shown that such compound streams can cause severe geomagnetic storms.

In the preceding section, we reported on the first announcement of a CME detected using the HI instruments, for the events of 24–26 January 2007. Using the HI observations of this event, which in fact appears to involve two distinct ejecta, Lugaz *et al.* (2008) also show that in-depth analysis of CME evolution using HI data can be performed effectively using numerical simulations of transients propagating in the solar wind. The authors demonstrated that these two CMEs interact with a CIR. Their analysis showed

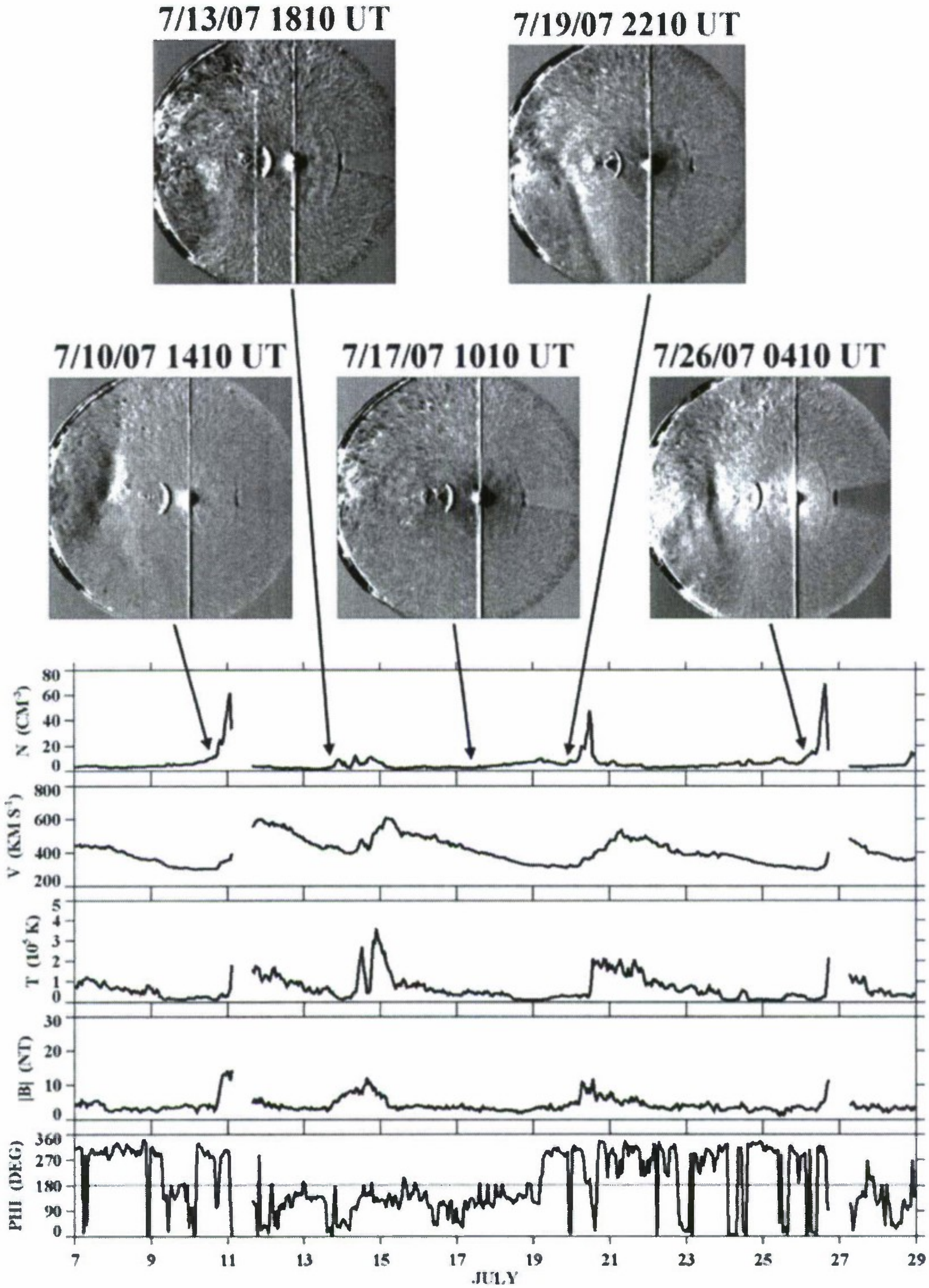

Figure 9 HI-2B images showing CIRs in the vicinity of the Earth in addition to *in situ* field and particle observations from the ACE spacecraft. (From Sheeley *et al.*, 2008b). Reproduced by permission of the AAS.

that CME-CIR interactions can occur before a CME propagates into the HI-2 fields of view and that numerical models can be used to simplify the interpretation of observations.

5. Planetary Impacts

A number of spacecraft present potential opportunities for studying, *in situ*, impacts on planets of solar mass ejection events detected in the HI data. Thus, researchers have considered the combination of HI observations with, for example, measurements from *Venus Express* (at Venus), *Mars Express* (at Mars), *Messenger* (flying by Venus and Mercury) as well as spacecraft near the Earth, such as ACE, SOHO, *Cluster*, *Wind* and *Themis*.

The first observations of impacts of HI-detected CMEs on a planetary system were made in the spring of 2007, with CMEs arriving in the vicinity of Venus. Rouillard *et al.* (2009a) presented the case of a CME propagating towards Venus in May 2007. The CME in question is shown in the lowest two panels of Figure 5. Figure 10 presents a composite of HI-1A and HI-2A images, showing Venus and a CME which impacted the planet, along with corresponding *in situ* observations made by *Venus Express*. This particular sequence is being studied in detail, given a particularly fortuitous spacecraft configuration, which not only includes *Venus Express* but also the *Messenger* spacecraft, which was on a Venus fly-by track.

Whilst this was a planetary-impacting CME, the combination and configuration of the spacecraft involved dictated that the emphasis of the study was more concerned with the unique measurements of the CME itself rather than the influence of the CME impact on the Venus system. Indeed, the Rouillard *et al.* (2009a) study demonstrated well that the

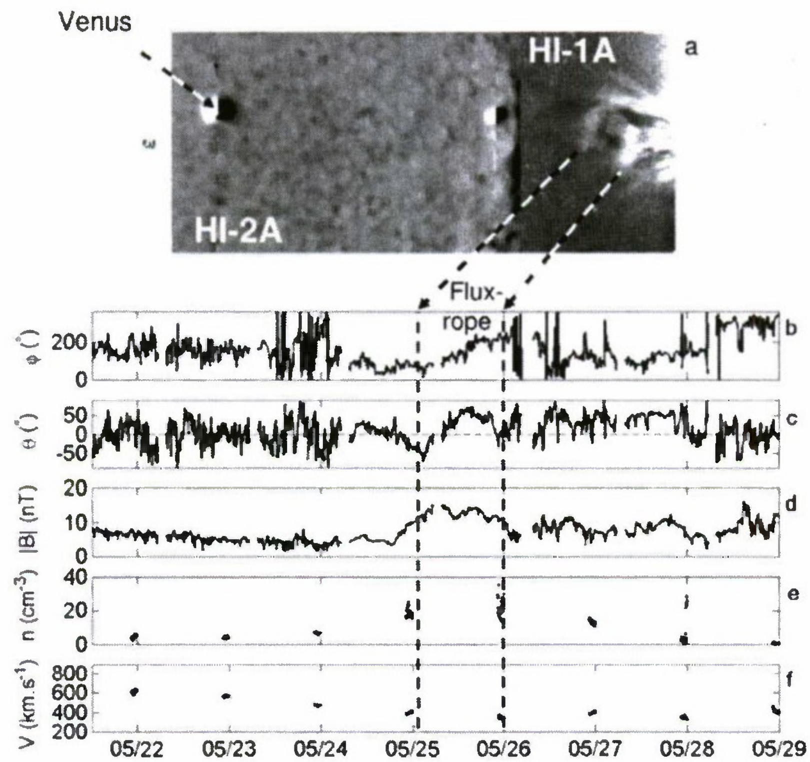

Figure 10 Panel a: a composite of running difference images from HI-1A and HI-2A. At this time, the CME can be seen in the HI-1A difference image, a few days before impacting Venus (seen in HI-2A). Panels (b, c, d): *Venus Express* magnetometer (MAG) measurements of the azimuth (panel b), elevation (panel c) and strength (panel d) of the magnetic field. Panels (e, f): density and speed of solar wind protons measured by the *Venus Express*-ASPERA-4 instrument. The flux rope of the CME observed *in situ* is bound by the arrival of the two dense regions seen in HI running difference images (vertical dashed line).

dynamics of CMEs can be studied in detail using HI and, in particular, the authors measured the radial expansion of the CME, noting that such detailed studies had been limited to *in situ* observations prior to the STEREO and SMEI missions. The expansion of a CME along the radial direction is associated with the tension forces acting to maintain the magnetic structure of the CME. This effect has important applications for the interpretation of the appearance of CMEs in white-light images. The expansion of the radial extent of a transient propagating in an ambient solar wind that expands along the heliocentric longitudinal and latitudinal dimensions (*i.e.* radial expansion) will force plasma to pile-up on the edges of the CME flux rope leading to the intensification of the CME brightness on the boundary of the flux-rope.

For completeness, we note that whilst we are considering planetary impacts, the CIR studies presented by Sheeley *et al.* (2008b), as discussed previously, are also relevant to the issue of planetary impacts. Figure 9 is a graphic example of the influence of CIRs on the near-Earth space environment.

6. Comets and Asteroids

As a by-product of the CME-related studies for which the HI instruments are designed, we have observations relevant to cometary and asteroid research. This is a natural consequence of such a sensitive wide-angle imaging system and there is a considerable heritage of such observations in coronagraph data (*e.g.* Biesecker *et al.*, 2002; Hoenig, 2006; Sekanina and Chodas, 2007). Indeed, the SOHO LASCO instrument detected its 1500th comet in June 2008. We also note that the HI cometary observations are complementary to those studies made using SMEI observations from 2004 (see *e.g.* Kuchar *et al.*, 2008; Buffington *et al.*, 2008).

Among the first observations made using the HI instruments was a spectacular sequence of images of comet McNaught, whose perihelion passage occurred on 12 January 2007 at a distance of 0.17 AU from the Sun. The comet displayed a huge, highly structured tail, as shown in Figure 11, an image taken almost immediately using HI-1B after opening the door of the instrument. Comets are valuable bodies for the investigation of composition of the solar nebula, from which our solar system formed. There are few observations relating to the metallic content of comet nuclei, mainly because the sublimation temperatures of these metals are such that we require observations close to the Sun, which are difficult to perform by traditional means. Fulle *et al.* (2007) examined the arch-like tail structure from the HI observations and compared the shape of the tail to computed shapes based on the motion of different atomic species. They found that the tail brightness and shape was best fitted by a neutral iron tail.

Of course, cometary observations of this kind provide basic information on comets themselves and on the solar wind environment. However, one particularly important feature of such aspects of the STEREO mission relates to CMEs-impact on solar system bodies. In that respect, Vourlidas *et al.* (2007) reported on the observation of a comet tail disconnection event due to a CME impact. During April 2007, comet Encke was seen to pass through the HI-A fields of view. On 20 April 2007 a CME passing through the HI-1A field of view appears to engulf the comet and we witness a complete disconnection of the comet plasma tail, as shown in Figure 12. Vourlidas *et al.* (2007) interpret the disconnection as being due to magnetic reconnection, occurring on the tail side of the comet, between the CME front and the interplanetary magnetic field draped around the comet. This observation is particularly relevant to the STEREO HI objectives in that it is a graphic display of the kinds of impacts we might expect on other solar system bodies, such as planets, on a somewhat reduced scale.

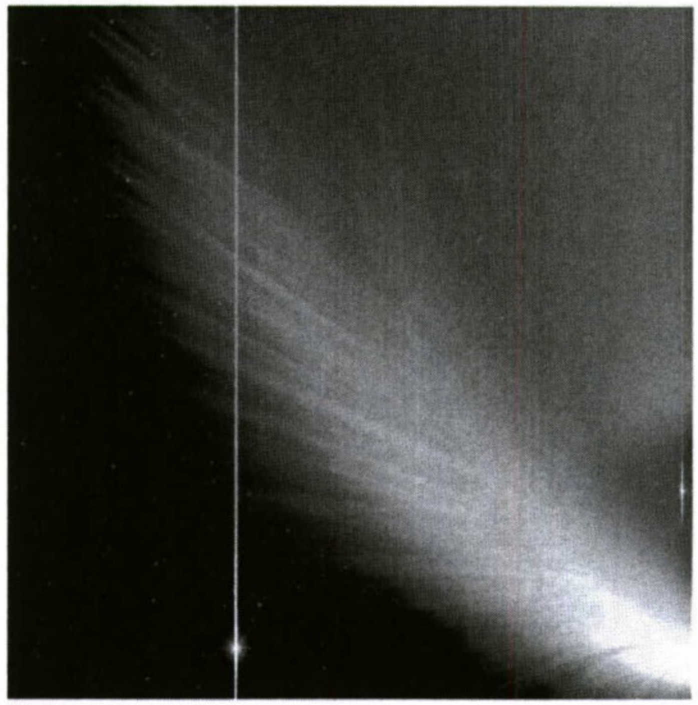

Figure 11 The highly structured comet McNaught tail as imaged using HI-1B shortly after opening the instrument door. The planets Venus (bottom of the frame) and Mercury (right hand side) show considerable blooming due to their brightness.

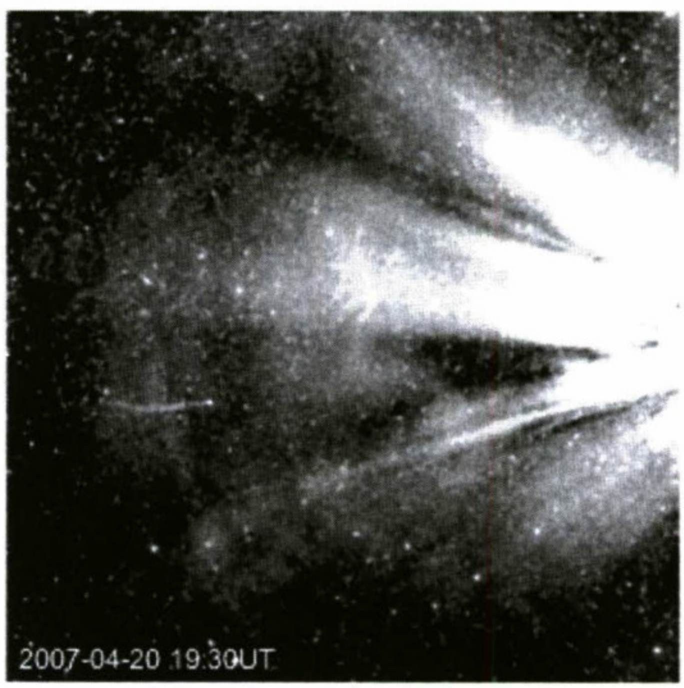

Figure 12 An HI-1A image showing comet Encke (centre – left) responding to an impact by a CME. The comet tail has been disconnected from the comet nucleus and in subsequent images was carried away from the nucleus in the solar wind flow.

There are many other examples of cometary observations in the HI data and a number of issues being studied at this time. However, the comet McNaught and comet Encke observations demonstrate the capacity of the HI instruments for such studies and provide a flavour of the work being undertaken.

On the other hand, with regard to asteroids, the interest in HI observations has been largely driven by public interest in near-Earth objects and it is well recognised that a wide-

angle imaging system is an excellent instrument for the identification of such objects. Indeed, many amateurs around the world are using HI data for identifying and discovering comets and asteroids and much of this is coordinated and catalogued through a dedicated website at http://sungrazer.nrl.navy.mil. In addition, we note that from an instrumental point of view, imaging point-like, weak-intensity objects is a useful exercise for understanding the instrument performance.

7. Heliospheric Imaging and IPS Observations

Interplanetary scintillation (IPS) observations have a long heritage in studies of the heliosphere and transient activity (*e.g.* Gapper *et al.*, 1982; Tappin, Hewish, and Gapper, 1984; Harrison *et al.*, 1992). Much of this work utilised the Cambridge 81.5 MHz array, which is no longer operational. However, an abundance of IPS work has emerged in recent years, especially using the European Incoherent SCATter (EISCAT) radar facility in northern Scandinavia (Rishbeth and Williams, 1985; Bourgois *et al.*, 1985; Wannberg *et al.*, 2002) and it is timely to combine this work with heliospheric imaging.

Dorrian *et al.* (2008) have presented simultaneous IPS and HI observations of a coronal mass ejection. During a 30-minute run of IPS observations, performed during May 2007 using the EISCAT UHF antennas, characteristic signatures of CME activity were evident. The plane-of-the-sky velocity derived from the IPS measurements was seen to increase over the half-hour interval, from around 420 to 520 $\mathrm{km\,s^{-1}}$. The location of the compact IPS radio source was such that the ray-path lay within the HI-1A field of view. The visible-light intensity near the IPS P-point (the point of closest approach of the IPS ray-path to the Sun) revealed that the IPS CME signatures corresponded to a region within a faint CME front observed by HI-1A. The authors suggest that this front may represent the merging of two converging CME structures with plane-of-the-sky velocities derived from the HI observations of 325 and 550 $\mathrm{km\,s^{-1}}$ for the trailing and leading fronts, respectively. These observations represent the first time that it has been possible to interpret IPS observations of small-scale structure within an interplanetary CME in terms of the global structure of the event.

8. Discussion

The HI investigations include a range of other topical areas which we have not reported on in detail here, mainly because these areas need more investigation to come to fruition or for the production of initial results. This includes a thorough analysis of the distribution of the F-corona. It also includes studies of signatures of CME onsets in the HI data, which are in an early phase of study but are reported in this issue (Harrison, Davis, and Davies, 2009). We also note developing studies of stellar oscillations using the HI data, exploiting the fact that the instruments provide long-term monitoring capabilities (*e.g.* Bewsher and White, private communication), as reported briefly by Brown, Bewsher, and Eyles (2009). We also look forward to a new phase in the operation of STEREO during the coming year, where the spacecraft configurations are better suited to 3-dimensional studies of CMEs imaged from both HI instruments, to the detection of CMEs impacting the Earth and to better configurations relative to ground-based IPS observation opportunities. At the time of writing, the spacecraft-Sun-Earth angles are approximately 40 degrees.

This review has described numerous research topics that have already demonstrated that the HI data are resulting in significant advances in the understanding of CME propagation

in the heliosphere, and of CME impacts with solar system bodies. The applications with regard to space weather are clearly evident. The study of non-solar phenomena, such as comets, provides an extra bonus.

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